Assessing Fan Flutter Stability in Presence of Inlet Distortion Using One-way and Two-way Coupled Methods

Gregory P. Herrick

LMS: Multiscale & Multiphysics Modeling Branch
Glenn Research Center
Cleveland, Ohio
Gregory.P.Herrick@nasa.gov

July 29, 2014

Acknowledgments

- This work was supported by the Fixed Wing Project:
  - Dr. Rubén Del Rosario, Manager
  - Dr. Michael D. Hathaway, Technical Lead
  - Mr. James F. Walker, Deputy Project Manager for Glenn Research Center
- The author appreciates many valuable discussions with Dr. Milind A. Bakhle of NASA Glenn Research Center.

Background: Boundary Layer Ingestion

- Smith, L. H., "Wake Ingestion Propulsion Benefits," *AIAA Journal of Propulsion and Power*, Vol. 9, No. 1, Jan-Feb 1993, pp. 74–82.

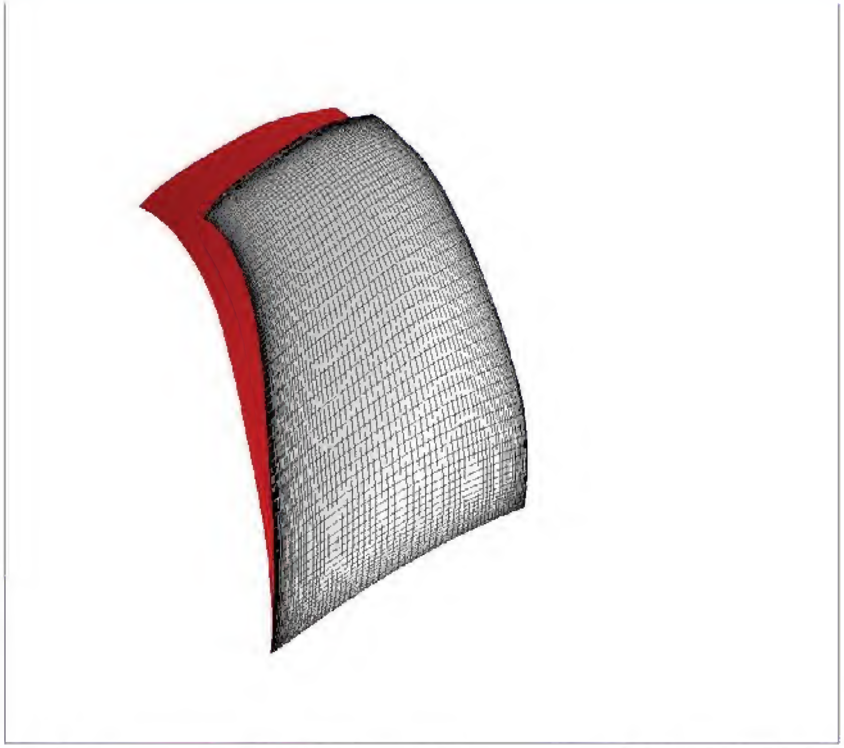
- Boundary Layer Ingestion (BLI) Propulsion has potential for significant reduction (5%-10%) in aircraft fuel burn.

- BLI may present significant flow distortion to fan. Aeromechanical response of fan in presence of distorted flow must be understood, and applied design must be aeromechanically robust.

CFD & Aeromechanics Code: TURBO-AE

- Unsteady Reynolds-Averaged Navier Stokes equations
- Characteristics-based finite-volume solver
- Newton-iterative, implicit, time-accurate
- Structured multi-block code
- Decoupled $k - \epsilon$ turbulence model
- Sliding interfaces where applicable
- Inlet distortion boundary condition
- Throttle exit boundary condition
- Dynamic grid deformation for blade vibration
  - One-way prescribed harmonic blade vibration (previously validated in aeromechanics analyses in clean flow and applied herein)
  - Two-way coupled blade motion (implemented and applied herein)

Computational Research Fan



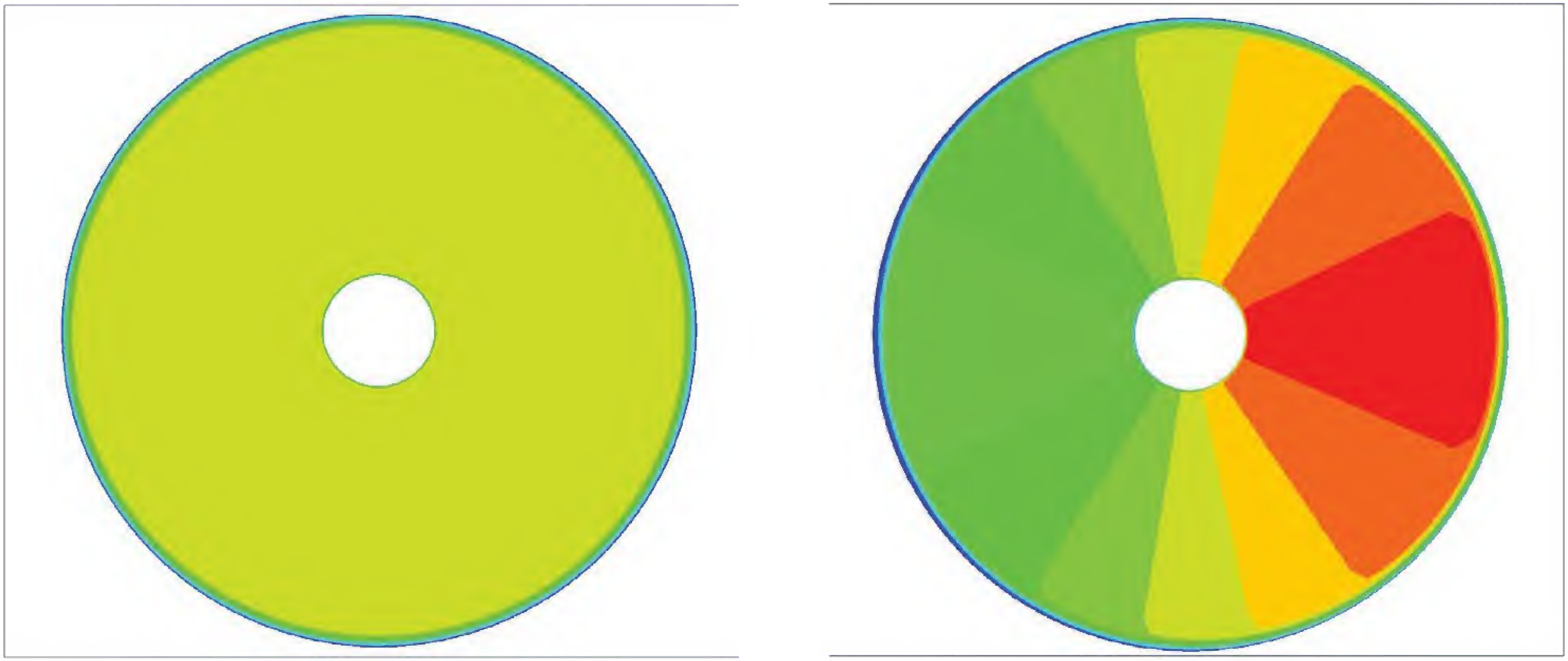
Passage Mesh	214/76/58
Blade Mesh	81/70/58
Inlet Duct Length[1]	1.387
Exit Duct Length[1]	2.365

Tip Diameter	22 in.
Blade Count	22
Rotor Speed[2]	10800 rpm
Blade Natural Frequency	220 Hz
Rotational Frequency	180 Hz
Time Steps/Passage	15
Time Steps/Revolution	330
Time Steps/Oscillation	270
Subiterations, Clean	6
Subiterations, Distorted	9
Clock per step, Clean	1m:16s
Clock per step, Distorted	1m:53s
Clock per rev, Clean	6h:58m
Clock per rev, Distorted	10h:21.5m

[1] axial chords at tip radius

[2] Part-speed condition studied here

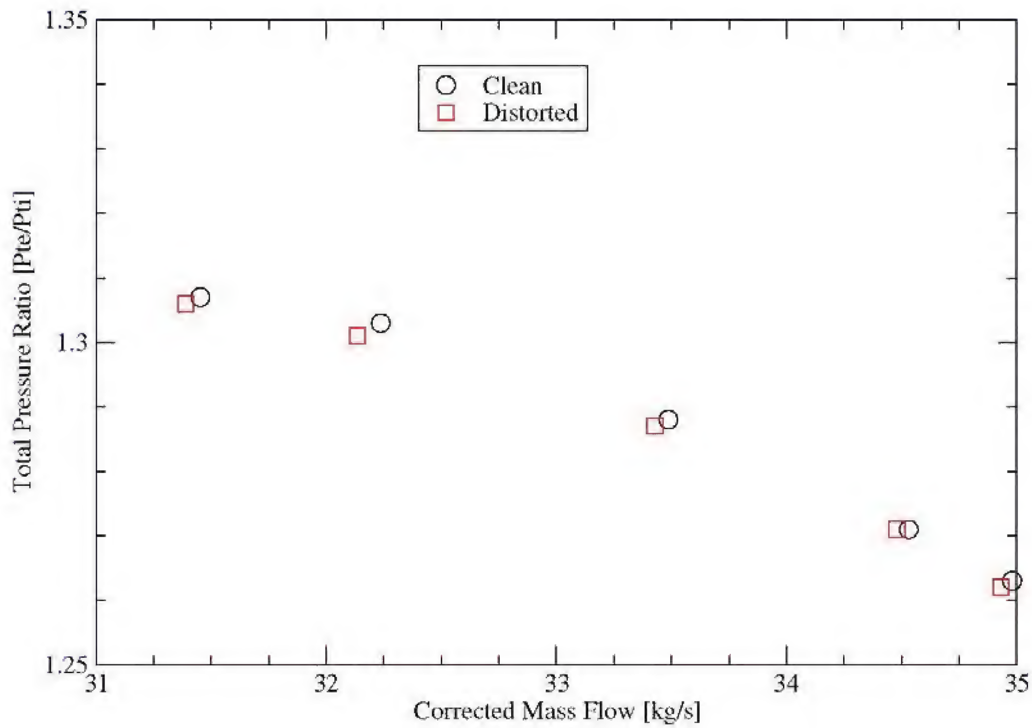
Inlet Total Pressure



- Clean Inlet
- Sinusoidal Inlet Distortion (4% mean-to-peak)

Azimuthal orientation: 0° at 12 o'clock, increasing clockwise. Fan rotates counterclockwise.

Rotor Part-Speed Performance Characteristics



- Speedlines for clean and distorted inlets.
  - Averaged over one revolution.
  - Distorted flow yields slight degradation in mass flow and pressure recovery.

One-way Coupling: Mathematics

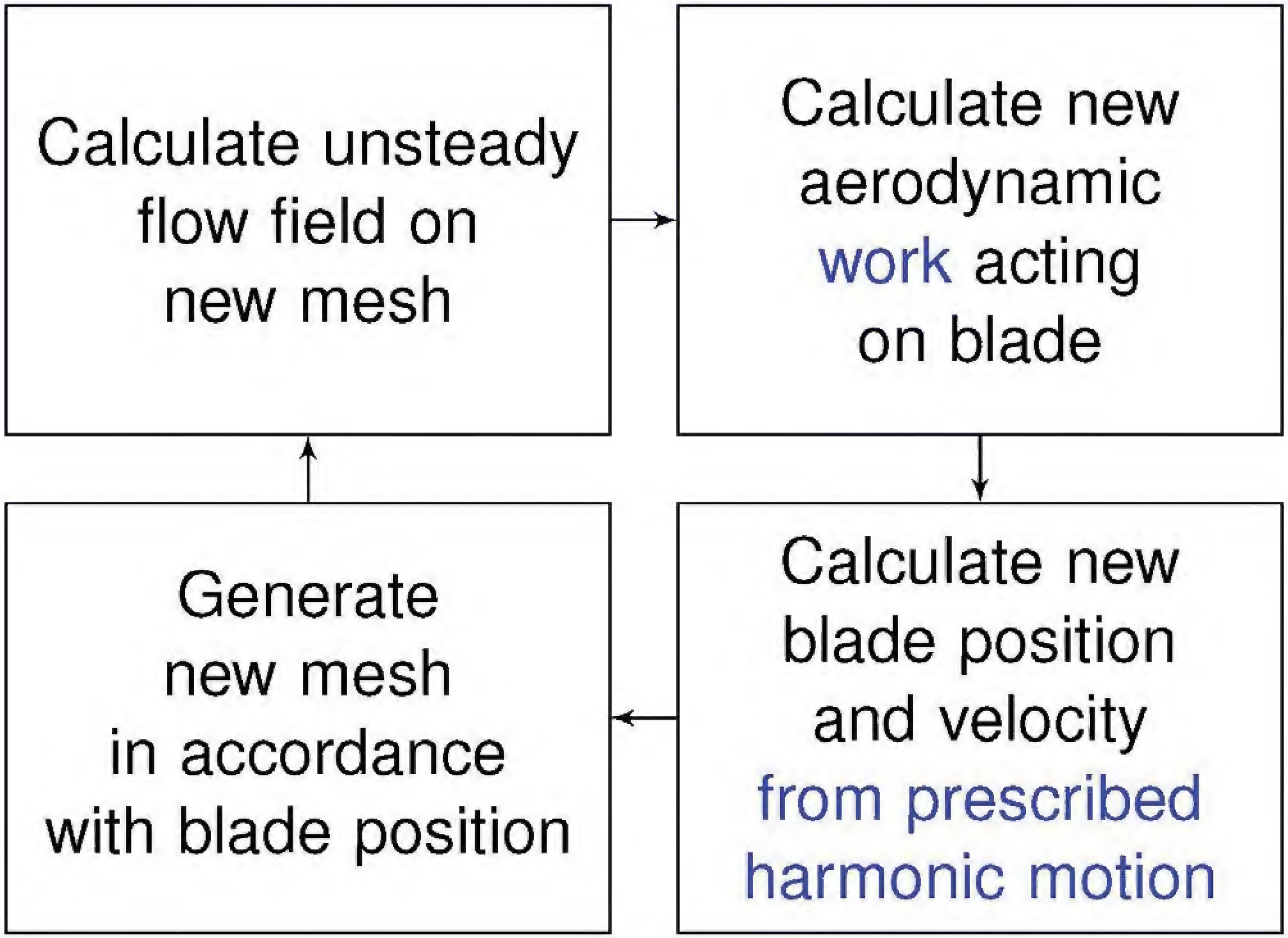
Blade vibrations are prescribed in a selected mode (Φ), *frequency* (f), and *nodal diameter* pattern (ND) or *inter-blade phase angle* (σ). The work done on the vibrating blade is calculated as follows:

$$W = -\oint \int_{surface} p\, d\vec{A} \cdot \frac{\partial \vec{X}}{\partial t}\, dt \qquad (1)$$

where p is the *aerodynamic pressure*, $\vec{A}$ is the *blade surface area vector*, $\vec{X}$ is the *displacement vector* on the blade surface, and t denotes *time*. The *aerodynamic damping ratio* (ζ) can be approximately related to the *work-per-cycle* (W) and the *average kinetic energy* (K_E) of the blade over one cycle of vibration through the following expression:

$$\zeta \approx -\frac{W}{8K_E} \qquad (2)$$

One-way Coupling: Time Marching Scheme

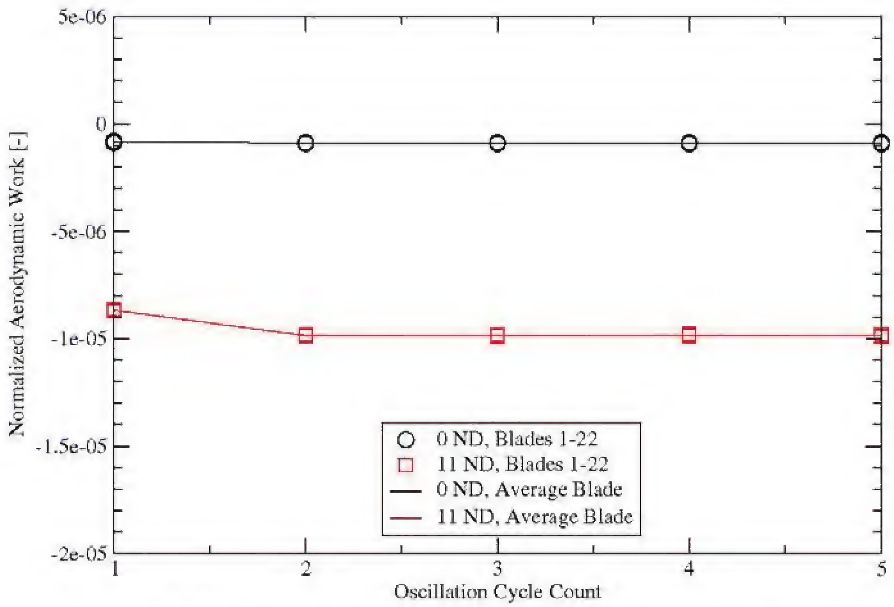


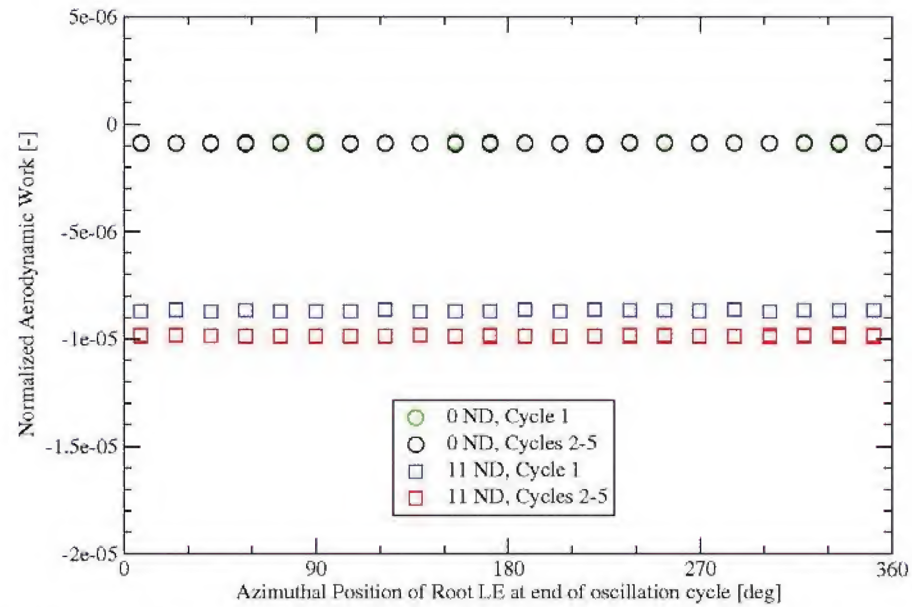
Aerodynamic damping is calculated from the aerodynamic work quantity. Positive aerodynamic work signifies negative aerodynamic damping and indicates the possibility of flutter.

One-way Coupling: Clean Inlet, Near Op-Line

Convergence of Aerodynamic Work for All 22 Blades

$\sigma = 0^\circ$ for 0 ND, and $\sigma = 180^\circ$ for 11 ND



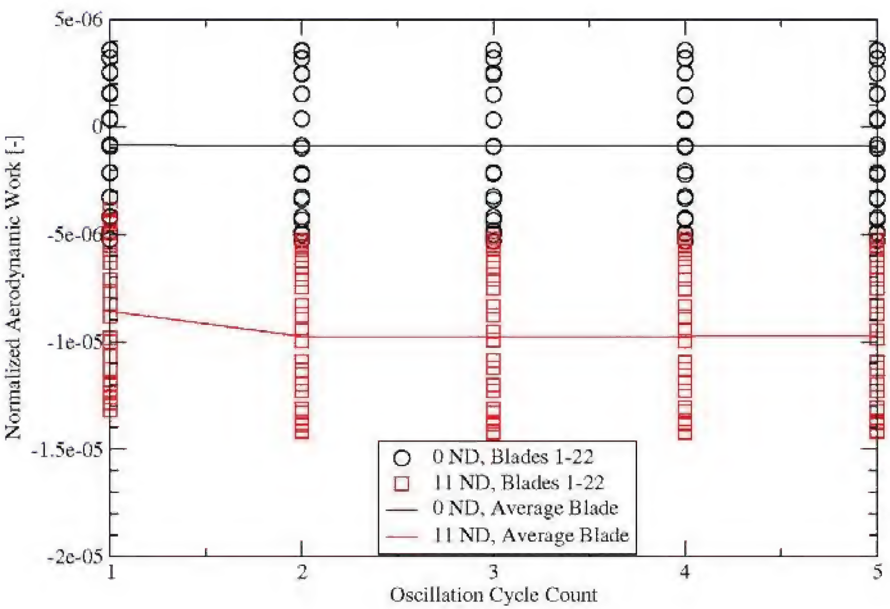


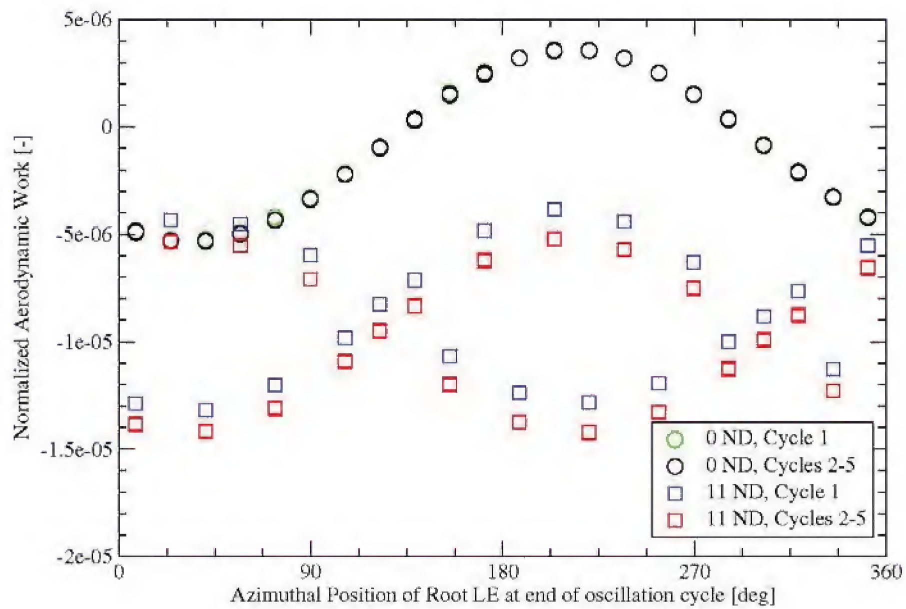
- May require a few cycles to converge (11 ND here)
- Consistent about annulus (clean inlet)

One-way Coupling: Distorted Inlet, Near Op-Line

Convergence of Aerodynamic Work for All 22 Blades

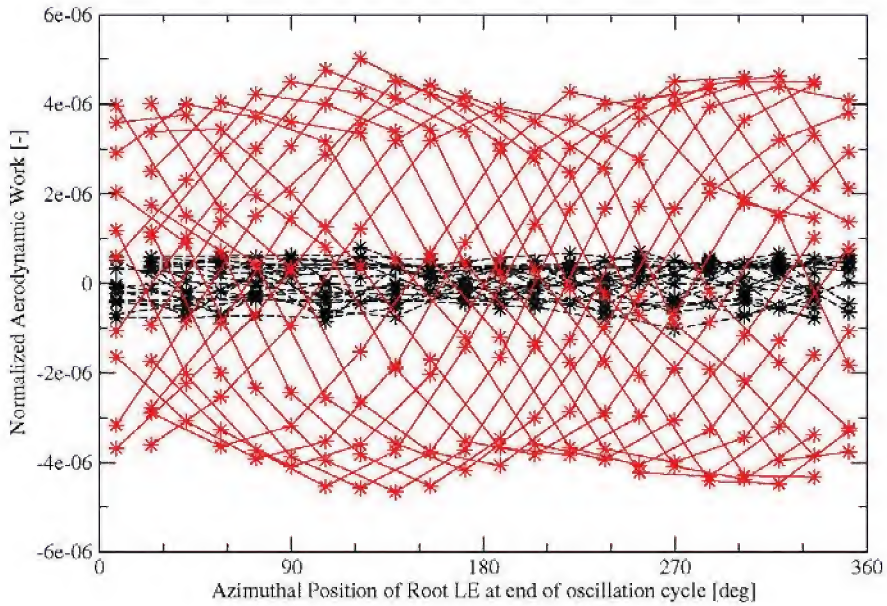
$\sigma = 0^\circ$ for 0 ND, and $\sigma = 180^\circ$ for 11 ND

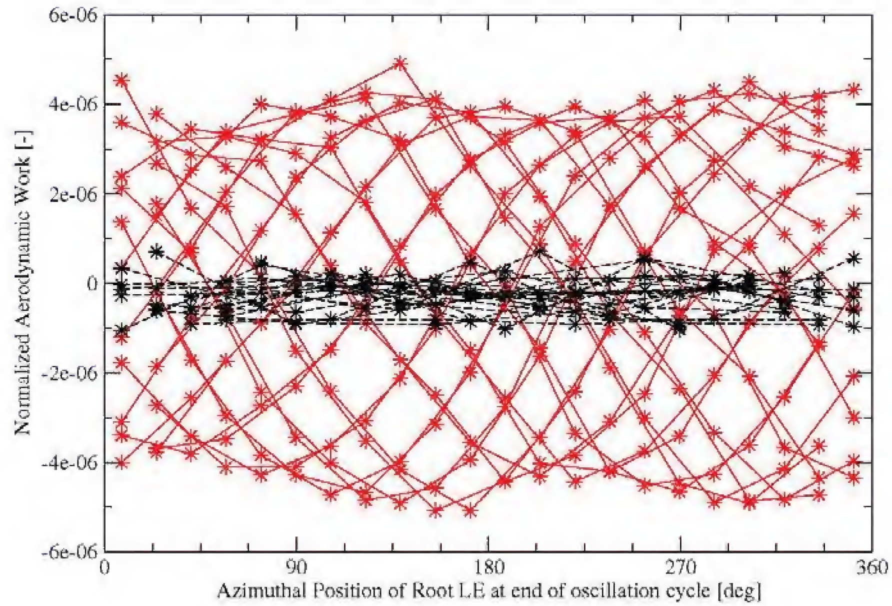




- May require a few cycles to converge (11 ND here)
- Work is a function of azimuthal position:
  - Unique for each subset of blades within each ND pattern
  - May exhibit mixed stability/instability (0 ND here)

One-way Coupling: Aerodynamic Work Versus Azimuthal Position

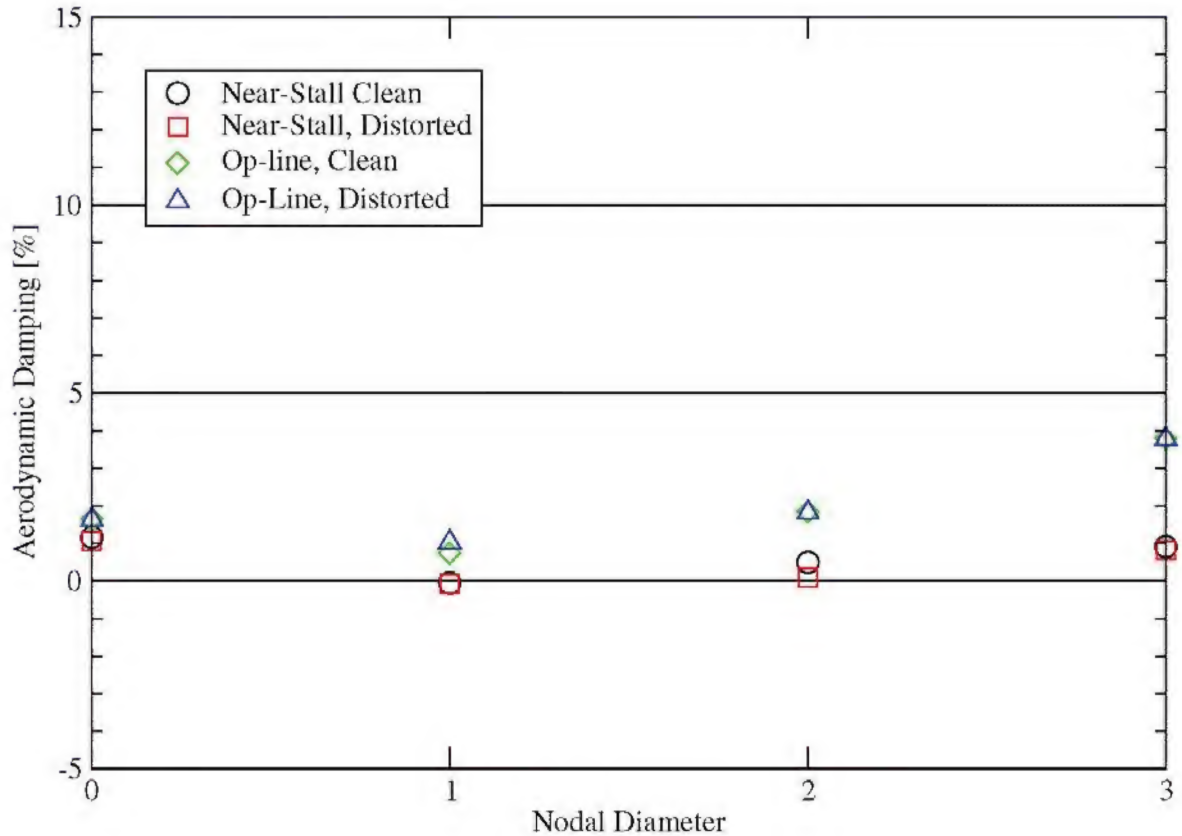




$\sigma = 16.36°$	1 ND
avg blade, clean	-0.068%
all blades, clean	mixed
avg blade, distorted	-0.072%
all blades, distorted	mixed

$\sigma = 32.73°$	2 ND
avg blade, clean	+0.49%
all blades, clean	mixed
avg blade, distorted	+0.09%
all blades, distorted	mixed

One-way Coupling: Nodal Diameter Sweep



- Aerodynamic damping versus nodal diameter using average-blade aerodynamic work from one-way coupled method.

Two-way Coupling: Mathematics

From the original equation of motion,

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\} - \{f_s\} \quad (3)$$

where

$$\{F\} = -\int_{surface} p\, d\vec{A} \quad (4)$$

Pre-multiply by the mode shape $[\Phi]^T$, establish the generalized displacement coordinate η, and normalize to unit modal mass:

$$[\Phi]^T[M][\Phi] = 1 \quad (5)$$

$$\{X\} = [\Phi]\{\eta\} \quad (6)$$

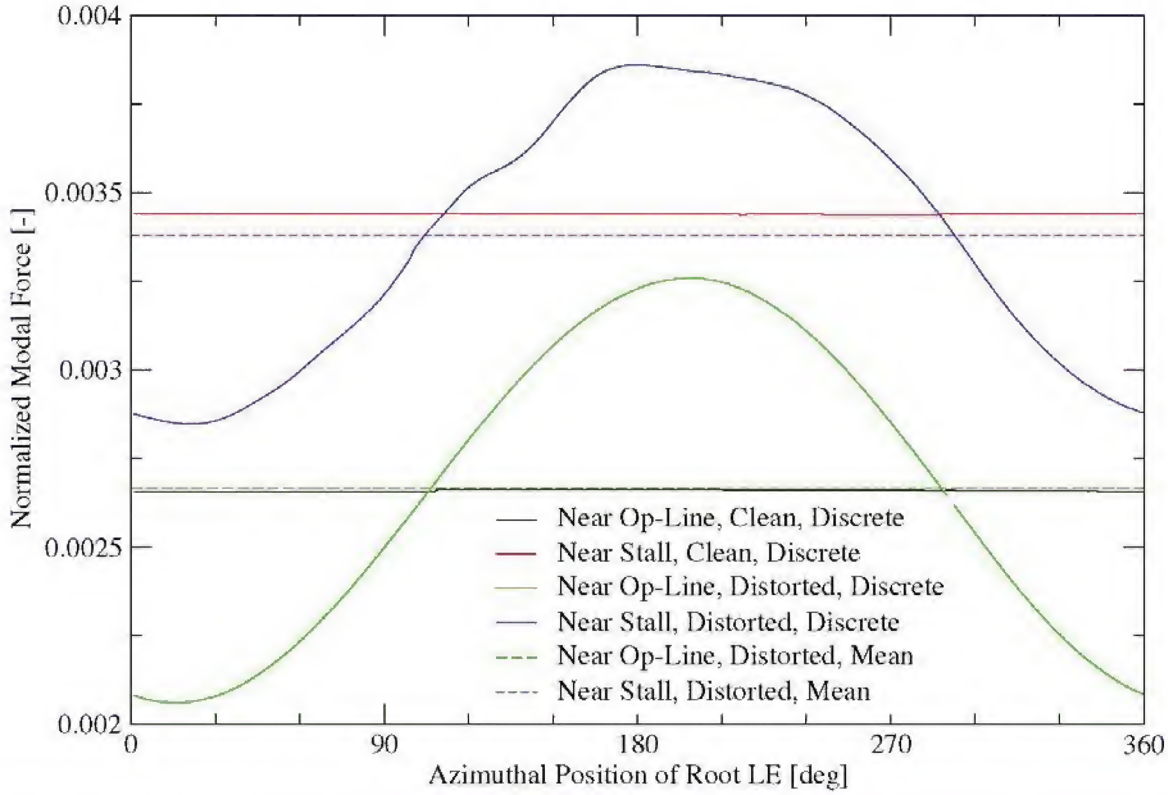
Applying the conservative simplification of neglecting material and structural damping (i.e., assuming $C = 0$) yields independent second order ordinary differential equations for each mode i:

$$\ddot{\eta}_i + \omega_i^2 \eta_i = [\Phi_i]^T\{F_i - f_{s,i}\} \quad (7)$$

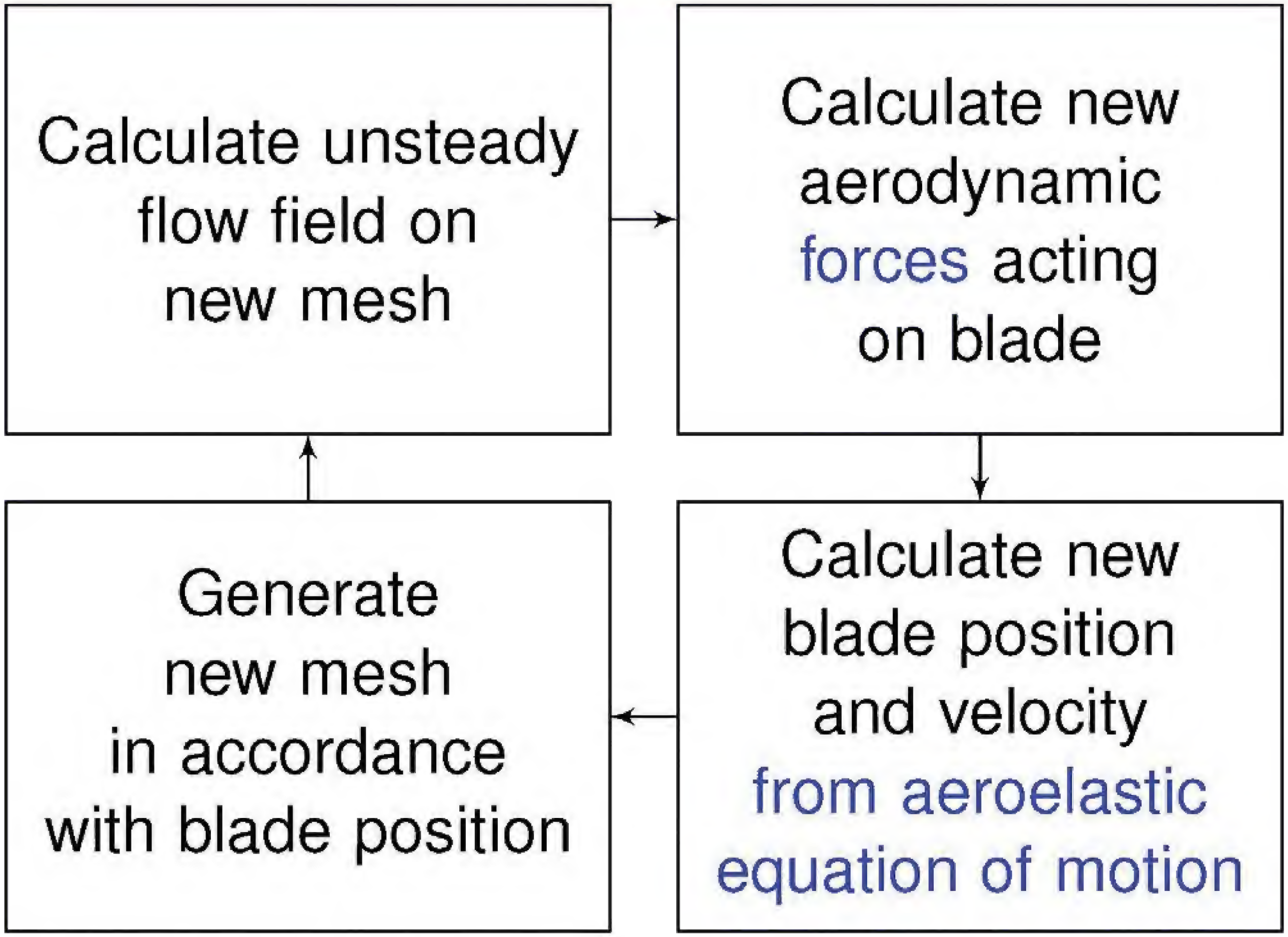
Two-way Coupling: "Static Modal Force"

- Static modal force: Modal force on rigid blades due to unsteady pressure loading of clean and distorted flows. One blade shown.

$$[\Phi_i]^T\{f_{s,i}\} = -\int_{surface} \Phi_i^T \cdot p\, d\vec{A} \tag{8}$$



Two-way Coupling: Time Marching Scheme

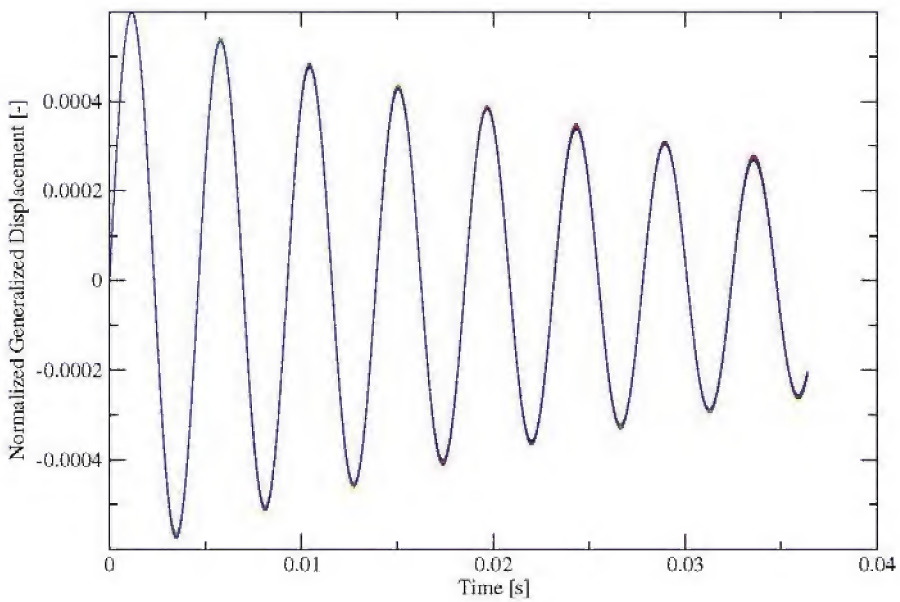


Aerodynamic damping is quantified by logarithmic-decrement analysis of blade modal displacements. Increasing magnitudes of displacements signify negative aerodynamic damping and indicate possibility of flutter.

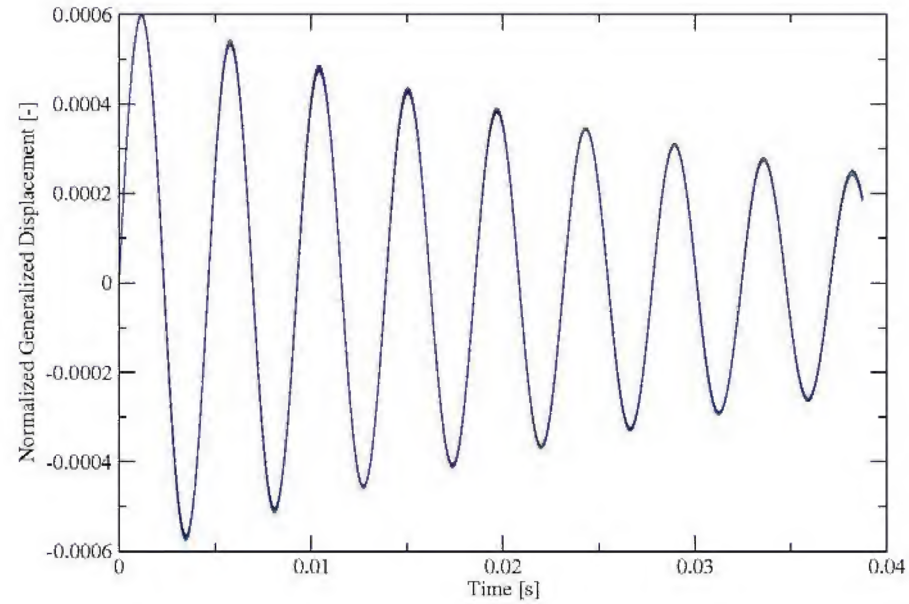
Two-way Coupling: Near op-line, 0 Nodal Diameter

All 22 Blades, $\sigma = 0^{\circ}$

- Clean inlet



- Distorted inlet

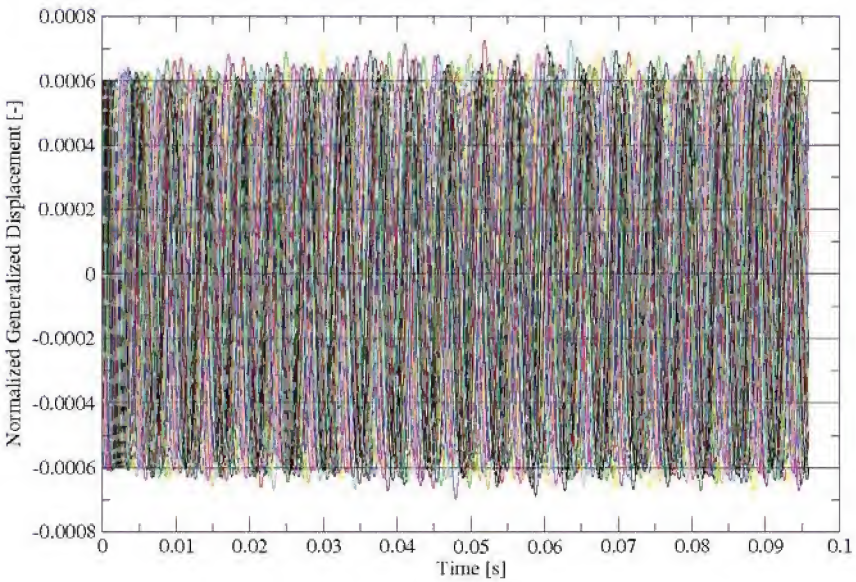


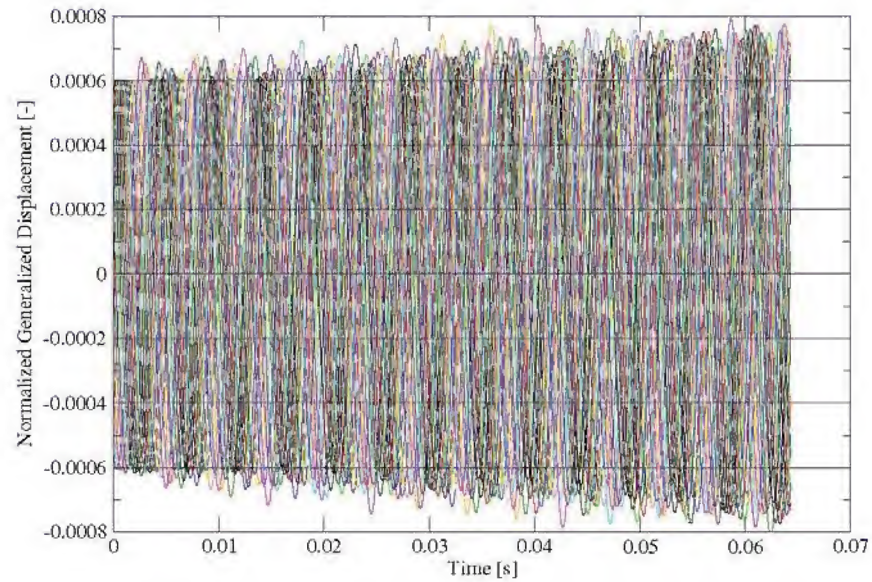
- Decreasing magnitudes of oscillation indicate flutter stability.
- Damping: One-way = +1.64%; Two-way = +1.60% to +1.80%.
- Clean and distorted inlets nearly-identically stable.

Two-way Coupling: Near stall, 1 ND FTW

All 22 Blades, $\sigma = 16.36°$

- Clean Inlet
- Distorted Inlet





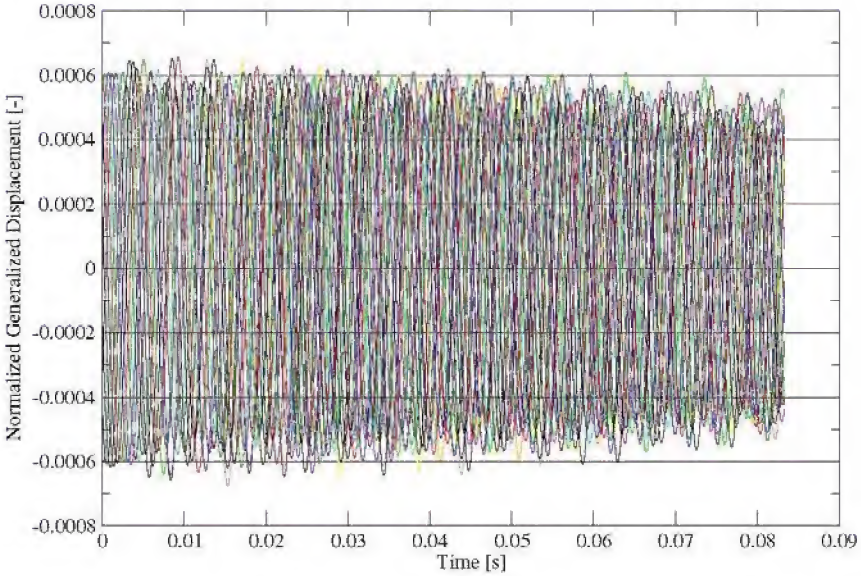
One-way avg blade	-0.068%
One-way all blades	mixed
Two-way coupled	$\approx$ -0.038%

One-way avg blade	-0.070%
One-way all blades	mixed
Two-way coupled	$\approx$ -0.20%

Two-way Coupling: Near stall, 2 ND FTW

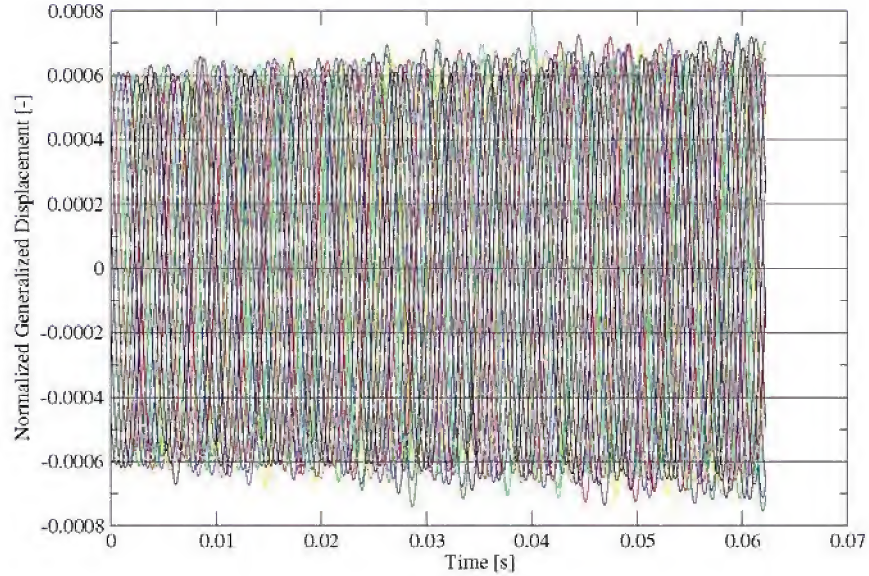
All 22 Blades, $\sigma = 32.73^\circ$

- Clean Inlet



One-way avg blade	+0.049%
One-way all blades	mixed
Two-way coupled	≈+0.014%

- Distorted Inlet



One-way avg blade	+0.09%
One-way all blades	mixed
Two-way coupled	≈-0.16%

Summary

- A two-way coupled flutter analysis method has been implemented in TURBO-AE.
- One-way and two-way coupled flutter analysis methods have been applied to study fan flutter in presence of inlet distortion (total pressure).
- Distortion defined as single, once-per-revolution distribution about annulus with a 4% (mean-to-peak) variation about clean inlet's radially-varying total pressure profile.
- Fan run at part-speed with artificial mode shape and natural frequency.

Conclusions

- Distorted flow conditions consistently yield slight degradations in mass flow, pressure recovery, and flutter stability versus the clean flow conditions of identical circumferential-mean total pressure distribution.
- Flow nonuniformity and nodal diameter pattern determine each blade's aerodynamic work response. Individual blade aerodynamic work response will vary *consistently about the annulus* from cycle to cycle due to interplay of blade natural frequency and rotor rotational frequency.

Conclusions – Continued

- Two-way coupled method corroborated one-way coupled method's average-blade flutter assessment when:
  - *all* blades showed stability about the whole annulus using one-way coupled method;
    OR
  - "average" blade showed *in*stability.
- For 2 ND FTW near stall:
  - One-way coupled method's average-blade showed stability in both clean and distorted flows.
  - Two-way couple method showed stability in clean flow but *in*stability in distorted flow.

Future Work

- Refined time-stepping, longer simulation times, refined gridding:
  - More clearly establish existence and magnitude of instabilities;
  - Interrogate higher-fidelity results to better understand fundamental aeromechanics. (incidence angle, shock position, e.g.)
- Improved fluid-structure time-coupling
- More realistic, more complete inlet distortion definition (swirl, e.g.)
- Physical experiment